



Furthering Advancements to Shorten the Time (FAST) to Commissioning for Pumped Storage Hydropower (PSH) Prize

Cooperative Research and Development Final Report

CRADA Number: CRD-19-00838

NREL Technical Contact: Michael Ingram

**NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-82311
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Suggested Citation

Ingram, Michael. 2022. *Furthering Advancements to Shorten the Time (FAST) to Commissioning for Pumped Storage Hydropower (PSH) Prize: Cooperative Research and Development Final Report, CRADA Number CRD-19-00838*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-82311. <https://www.nrel.gov/docs/fy22osti/82311.pdf>.

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Cooperative Research and Development Final Report

Report Date: February 28, 2022

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Southwest Research Institute

CRADA Number: CRD-19-00838

CRADA Title: Furthering Advancements to Shorten the Time (FAST) to Commissioning for Pumped Storage Hydropower (PSH) Prize

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Sponsoring DOE Program Office(s): Office of Energy Efficiency and Renewable Energy (EERE), Water Power Technologies Office (WPTO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL & ANL Shared Resources/k/a Government In-Kind
Year 1	\$115,000.00
TOTALS	\$115,000.00

Executive Summary of CRADA Work:

NREL initiated a prize with support from Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL), and sponsored by the U.S. Department of Energy Water Power Technologies Office (DOE WPTO) to encourage ideas to reduce the time to commissioning for PSH projects. As a result, Southwest Research Institute (SWRI) was chosen as one of nine finalists to develop their concept in advance of the FAST Prize Pitch Contest held on October 27, 2021. The National Labs provided technical and business advisement to SWRI in preparation for this Pitch Contest.

Summary of Research Results:

The intent of this project was to investigate the application of steel dams for accelerating the development of new pumped-storage hydro (PSH) projects.

This investigation included cost comparisons of conventional dams to a fixed steel dam for a large closed-loop PSH facility designed for a site in the Southwest. Below is a summary of the tasks outlined in the Statement of Work and the results that were generated.

Task 1: Technical and business support provided by the National Laboratories to develop finalist concepts in advance of (final out-briefing) *FAST Forward* (October 27, 2021).

To accelerate pumped storage hydropower development, Southwest Research Institute (SWRI) has developed a modern version of a 19th-century steel structural dam to impound water in a reservoir. SWRI produced and published a video presentation depicting the concept: a circular dam, composed of modular sections that can be rapidly assembled using steel support frames made of industry standard beams [Southwest Research Institute, 2019].

Team Wittmeyer-Dasgupta of the Southwest Research Institute (SWRI) won for a modular steel concept for dams that reduces costs by one-third and cuts construction schedules in half.

The team, with technical and business support from NREL and Argonne National Laboratory, examined hypothetical steel dam designs for the upper reservoir on Gordon Butte in Montana. The team produced designs for steel dams of two different heights—80 feet and 100 feet. They also generated estimates of the total weight of structural steel required for each design, as well as the number of necessary steel supports and face plates. Comparison of *traditional* upper reservoir capital costs and construction times are compared with steel dam design in Table 1.

Table 1. Comparisons of Upper Reservoir Capital Cost and Construction Time

Dam Type	Volume or Weight	Capital Cost	Construction Time
Large 690 MW Eight-Hour Pumped Storage Hydropower Facility			
Roller-Compacted Concrete	2,000,000 CY	\$340 million ^a	1-2 years
Rock Fill	4,500,000 CY	\$153 million ^b	1-4 years
Steel Dam	55,000 t	\$83-\$100 million ^c	4-6 months
^a \$170/CY RCC emplacement cost based on reconstruction of Taum Sauk upper reservoir. ^b \$34/CY rock excavation cost [Witt et al. (2016), Table 10] ^c \$500-600/t for raw steel × 3 = \$1500-1800/t of structural steel fabricated and assembled			

Collaborating with NREL and ANL, SWRI advanced a low-cost, low-technology modular PSH design that can compete with small grid-scale battery energy storage systems using lithium-ion technology. The team combined low-weight prefabricated modular steel dams transported by flatbed trailer with low-cost Pumps-As-Turbines (PAT) power units. The resulting approach is estimated to limit capital expenditures per unit of energy to \$100–200/kWh. The availability of a 10 MW, 100 MWh PSH unit that can be built in a year for \$10 million could reinvigorate the PSH industry and bolster the resilience of the national grid. [Allison, 2021]

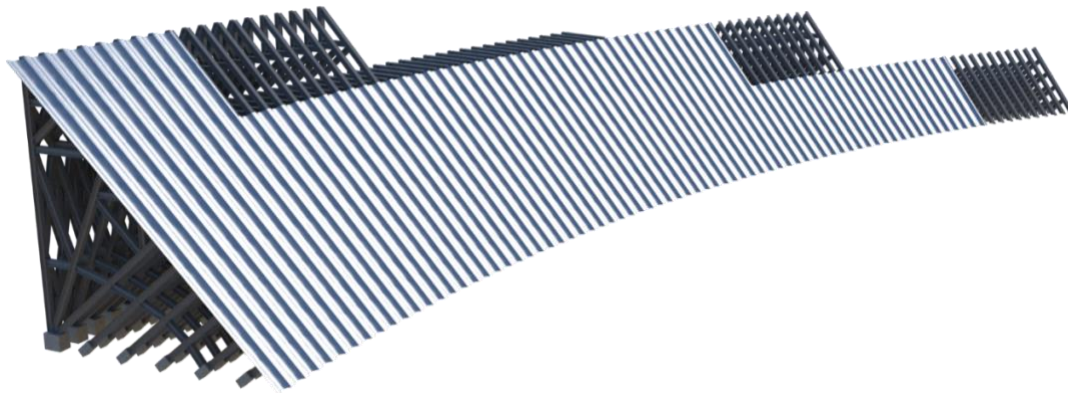


Figure 1. Modular assembly of large steel dam

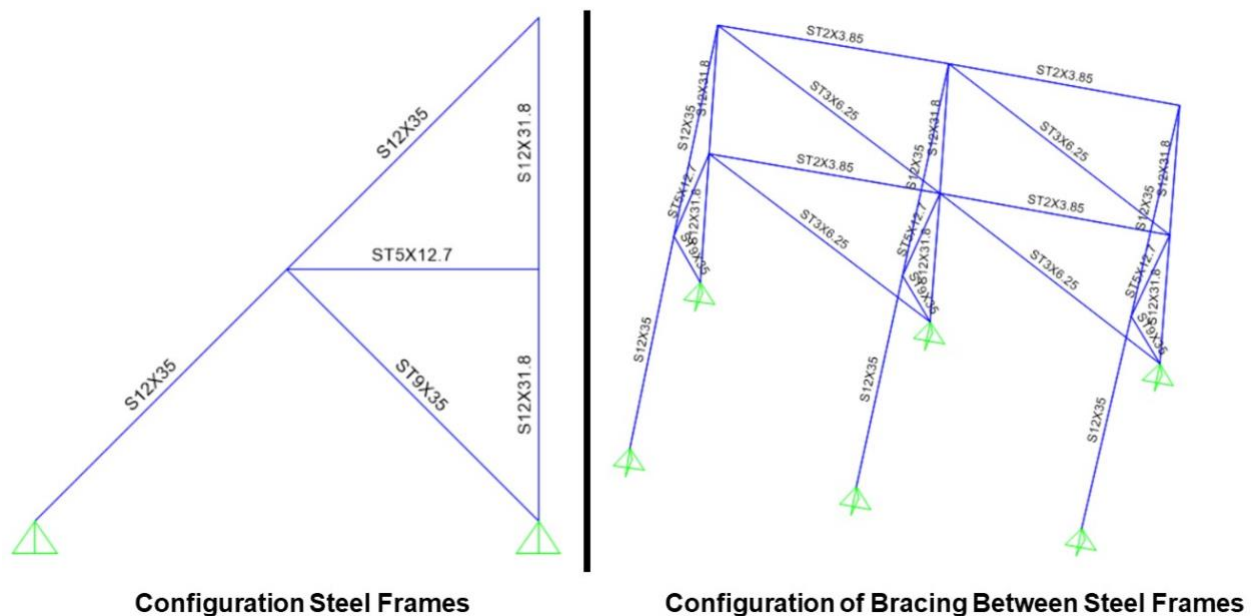


Figure 2. Structural Model Frame Design using SAP2000 (CSI, 2021)

Task 2: Support with preparation of the Pitch Day materials.

Team Wittmeyer-Dasgupta delivered the FAST Forward presentation on October 27, 2021, shown in Figures 3-9.

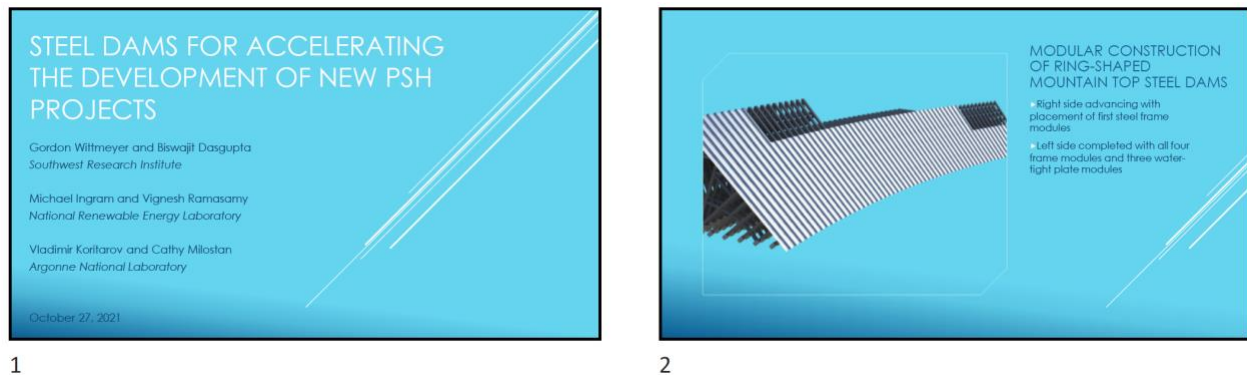


Figure 3. FAST Forward presentation, Slides 1 & 2 [Wittmeyer, 2021]

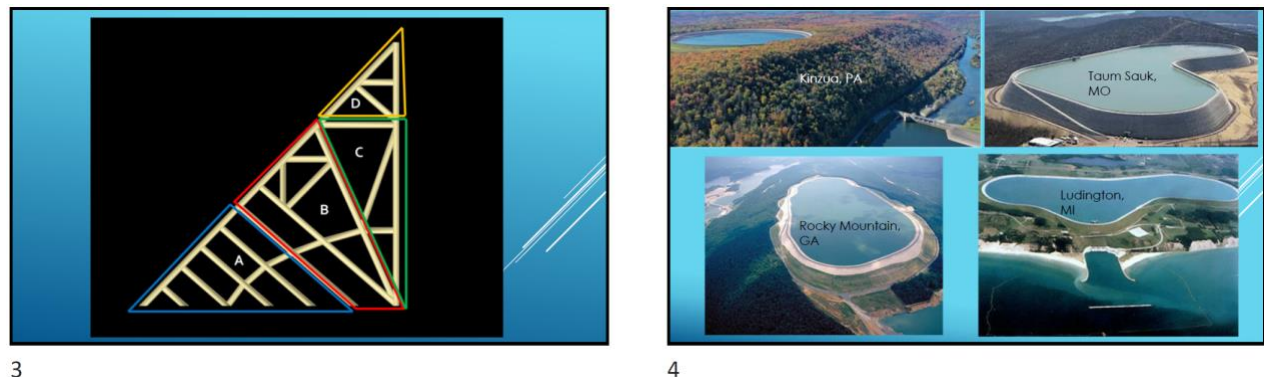


Figure 4. FAST Forward presentation, Slides 3 & 4 [Wittmeyer, 2021]

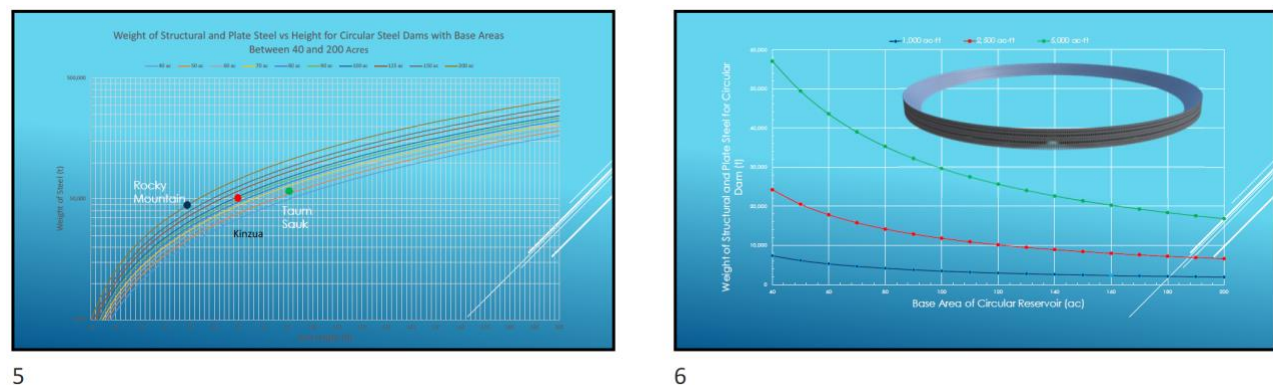


Figure 5. FAST Forward presentation, Slides 5 & 6 [Wittmeyer, 2021]

Current PSH Dams Compared to Equivalent Steel Dams			
	Rocky Mountain	Taum Sauk	Kinzua (Seneca)
Height (ft)	80	92	115
Length (ft)	12,800	6,660	7,800
Surface Area (ac)	210	55	110
Reservoir Volume (ac-ft)	10,200	4,350	5,756
Dam Material	Earthfill	RCC	Rockfill
Dam Volume (yd ³)	10,738,000	3,750,000	268,000,000 (???)
Dam Cost (2020)	\$215 million	\$490 million	(???)
	Steel Dam	Steel Dam	Steel Dam
Height (ft)	50	92	70
Weight of Steel (t)	40,000	60,000	50,000
Dam Cost (2020)	\$80 million	\$120 million	\$100 million

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Proposed Demonstration Project

PSH alternative to 10 to 100MW BESS units being installed in the ERCOT market

PSH should provide 4 to 8 hours duration instead of typical 1 to 3 hours from BESS

Target CAPEX of \$200 to \$250 per kWh to compete with utility-scale Li-Ion BESS [Feldman et al. (2021)]: \$341/kWh and \$1.365/kWh, \$2019]

Target sites that can accommodate larger diameter, shorter-height circular steel dams to take advantage of minimum impoundment expense per unit energy stored

Design steel dam supports and plate systems to be built at the fabricator, transported by truck on the interstate highway system, and assembled with low-capacity lifts on site.

Use commercial off-the-shelf centrifugal pumps as turbines (PATs) to reduce CAPEX and order times

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Figure 6. FAST Forward presentation, Slides 7 & 8 [Wittmeyer, 2021]

Big Harkey Canyon PSH Project Specifications

Upper Reservoir
Diameter = 666 ft
Depth = 10 ft
Max volume = 320 ac-ft
Max water level = 3,025 ft amsl
Min water level = 3,015 ft amsl

Lower Reservoir
Diameter = 1,800 ft
Depth = 10 ft
Max volume = 580 ac-ft
Max water level = 2,381 ft amsl
Min water level = 2,371 ft amsl
Pump inlets at 2,311 ft amsl

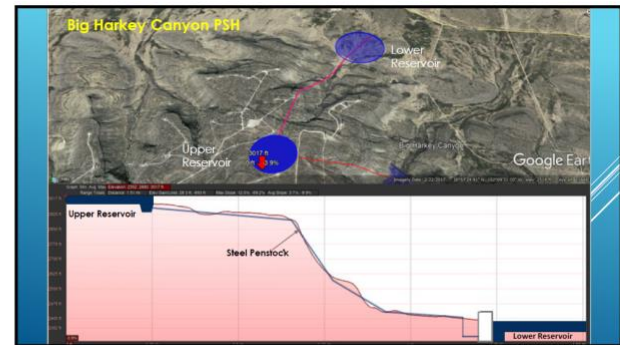
Rated Head = 613 ft
Head race and surface conduit 4,700 ft
Vertical shaft 90 ft

Discharge (8.6 hr) 550 cfs; 4 x 5 MW = 20 MW
Fill time 11.8 hrs; 4 x 5 MW

Energy required to fill = 235 MWh ($\eta=85\%$)
Energy recovered = 177 MWh ($\eta=85\%$)
Round trip efficiency 72%

Conduit is 96 in diameter; Velocity of 11 fps

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Figure 7. FAST Forward presentation, Slides 9 & 10 [Wittmeyer, 2021]

Design of Steel Structure and Concrete Foundations Optimized to Reduce Material Costs and Speed Assembly

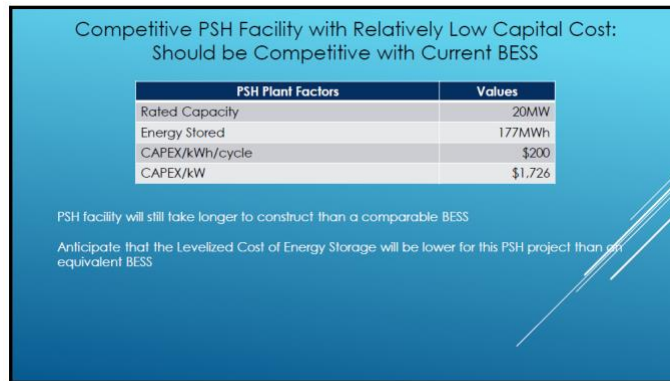
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General Bottom-Up Cost Model Developed to Estimate CAPEX for Big Harkey Canyon Demonstration PSH Project

Element	Cost (\$)
Site Staging and Preparation	\$2,287,015
Upper Reservoir	\$5,041,564
Lower Reservoir	\$5,464,176
Penstocks, Gates, Hoist, Trash Rocks	\$3,283,449
Pumps, Electromechanical Controls, Substation	\$4,079,754
Transmission, Permitting and Interconnection	\$4,388,202
Sales Tax	\$1,006,715
Contingency (25%)	\$6,387,719
Developer Overhead (6%)	\$1,916,316
Profit (5%)	\$1,692,745
Total	\$35,547,655

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Figure 8. FAST Forward presentation, Slides 11 & 12 [Wittmeyer, 2021]



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Figure 9. FAST Forward presentation, Slide 13 [Wittmeyer, 2021]

Task 3: Final report, to include a list of Subject Inventions; and other scientific and technical information in any format or medium that is produced as a result of this CRADA

This report is the Final report for this task.

Task 4 – National Renewable Energy Laboratory Technical Support

NREL developed and contributed a *bottom-up modeling method* to estimate the capital costs associated with PSH for a given site’s characteristics and system design. This approach involved mapping all key steps in the installation process and determining the labor, materials, and equipment required for each step. Overhead costs and profit were included, but project financing costs were not included in the upfront system cost estimates. Results applied U.S. cost assumptions for labor (Bureau of Labor Statistics 2021, www.bls.gov). The following are key system cost categories included in NREL’s contributed analysis:

- **Site Staging:** Selecting the optimal site is key for any hydropower station. Site staging costs include preconstruction survey, geotechnical investigation, temporary construction support buildings (i.e., offices, tool sheds, etc.) and construction site fencing.
- **Site Preparation:** Before the actual construction begins, the site needs to be prepared. In the cost model NREL estimated the cost of site preparation including clearing and grubbing, site grading, and excavation.
- **Structural Balance of System (SBOS):** SBOS includes the tonnage of heavy structures (triangular steel frames, rock anchors and rebars), hours of heavy equipment (i.e., hydraulic cranes), and volume of concrete for foundations.
- **Electrical Balance of System (EBOS):** Based on the kV and kVA ratings of the plant the cost of substation equipment including transformer, voltage regulator and service metering are estimated.
- **Permitting and Interconnection:** Based on the average cost per MWAC for a given project size class as detailed in Bird et al. (2018) and a fixed average permitting cost based on the approach detailed in Feldman et al. (2021).
- **Soft Costs:** Soft costs included sales tax (6%); contingency (25%); developer overhead (6%); engineering, procurement, and construction (EPC) overhead (8.3%), and profit markup (5%). The PHS system cost model assumes a higher contingency rate of 20% due to its relative newness.

A summary of capital cost of civil works, engineering, and equipment as well as sales tax, contingency, EPC overhead, and owner’s profit is provided in Table 2. For comparing the capital cost of this or similar PSH facilities to battery energy storage facilities the capital cost divided by plant generation capacity in MW and the capital cost divided by the energy injected to grid are presented in Table 3.

Table 2. Summary of capital cost

Cost of Major Components for Big Harkey Canyon PSH Facility	Estimated Cost (\$)
Site Staging and Preparation	\$1,809,881
Upper Reservoir	\$3,468,280
Lower Reservoir	\$3,307,973
Penstocks, Gates, Hoist, Trash Racks	\$2,818,591
Centrifugal Pumps, Electromechanical Controls, Substation	\$4,275,488
Transmission, Permitting and Interconnection	\$3,157,080
Sales Tax	\$807,611
Contingency (25%)	\$4,911,226
Developer Overhead (6%)	\$1,473,368
Profit (5%)	\$1,301,475
Total	\$27,330,972

Table 3. Per unit capital cost for comparative purposes

Capital Cost Summary for Big Harkey Canyon PSH Facility	
Rated Capacity	20 MW
Energy Injected to Grid/Cycle	171 MWh
CAPEX/kWh/Cycle	\$160/kWh
CAPEX/kW	\$1,598/kW

Task 5 – Argonne National Laboratory Technical Support

Argonne performed a preliminary market analysis to estimate the potential market size for steel dam PSH technology in the United States and highlight key advantages and disadvantages of this technology compared to conventional techniques for PSH dam construction. This section summarizes the key findings of their market analysis¹ which includes 1) market for new PSH innovations, 2) opportunities and competitive advantages of structural steel dams for PSH, and 3) potential challenges and responses to the use of steel dams for reservoirs for PSH plants.

5.1. Market for innovations to accelerate PSH growth for long-duration energy storage

DOE-WPTO's January 2021 report, U.S. Hydropower Market Report, states that PSH remains the “preferred least cost technology option for 4-16 hours duration storage” with 67 new PSH projects for total proposed capacity of 52 gigawatts (GW) under various stages of evaluation or development across 21 states in the U.S. The DOE report asserts that hydropower's electricity generating capacity can sustainably add 50 GW of new hydropower capacity by 2050, of which 36 GW in PSH plants.

However, development of new PSH projects face potential delays to site, construct and commission a PSH plant. In response to these barriers, the SWRI FAST team states that using modern steel dam design and modular steel construction methods for reservoirs for PSH plants has the potential to lower costs and shorten time to construct PSH reservoirs with opportunities to develop closed-loop PSH facilities in more environmentally-approved locations closer to energy demand centers.

5.2. Opportunities and competitive advantages of using steel dams for new PSH

Advantages of steel dams over conventional masonry, concrete and embankment dams include: 1) lower construction cost; 2) shorter construction times and 3) improved physical access to critical dam structures to facilitate maintenance and inspection.

Potential construction time savings from fabricating triangular steel frame structures in the factory and transporting via trucks to reservoir sites. Recent experience with modular construction methods for buildings have demonstrated consistent reduction in construction times. In a June 2019 McKinsey & Company study, “Modular construction: From projects to products” (2019), recent modular construction of buildings has ‘established a solid track record of accelerating project timelines by 20–50 percent’ with the potential to “realize more than 20 percent in construction cost savings”.

5.3. Potential challenges and responses

Potential challenges to using steel dams for PSH reservoirs include factors extending construction costs and time caused by supply chain concerns and material costs, labor issues, environmental, inspection and other government/regulatory approvals.

¹ Note that all findings of the market analysis should be considered preliminary and indicative because the budget limitations did not allow for a full-scale market analysis to be performed at this stage of the project.

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Subject Inventions Listing:

None

ROI #:

None